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ECL-281

DESIGN OF A VERTICALLY FLOATING BOAT HOOK

I was asked by the owner of a custom wooden boat shop to help in designing a boat hook which was to be a proper hook, i.e., one which would float vertically when dropped overboard. A vertically floating boat hook can be easily retrieved. It sounded simple but, as so often happens, the apparently simple things are not always simple.

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DESIGN OF A VERTICALLY FLOATING BOAT HOOK

PART A - INTRODUCTION

The proprietor of a custom wooden boat shop asked me if I could help in designing a simple device, a boat hook, but it was to be a *proper* boat hook. He and I both recalled an article(1) in a magazine discussing this device but details were forgotten except for a definition: *A proper boat hook is an ordinary boat hook designed to float in a vertical attitude with adequate above-water exposure so that it may be easily retrieved when dropped overboard.* A first impulse was, no problem! Take any buoyant spar, weight down one end to shift the CG off center, its weighted end should then submerge causing the device to float upright in the water. But, upon reflection, all boat hooks fit this simple description and not one we could find floated upright.

We now realized this design problem was not trivial, particularly if an optimum above-water exposure was desired. The referenced article was not very helpful as it offered only a trial and error approach we wanted to avoid. There ought to be a better way. One way might have been to muster computer power, but images of computer wire frame models of sticks and numerical answers of obscure origins made this approach unappealing. Application of hydrostatics principles as found in beginning chapters of any fluid mechanics text(2) will provide insight and solutions. The problem is geometrically one-dimensional, hence easily handled, and involves no advanced concepts.

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(1) *Jon Wilson; "The Proper Boat Hook - A Matter of Balance and Buoyancy"; Wooden Boat No. 71; Jul/Aug 1986; pp 25-27.*

(2) *V. L. Streeter; Fluid Mechanics, 6th ed.; McGraw-Hill; 1975.*

The Analysis Model

Direct application of hydrostatic principles not only provides answers but has the added benefit of showing that only two dimensionless parameters are important. When these are known the stability of spars of various lengths and the maximum attainable above-water exposure are immediately predictable. Our analysis model, shown in Fig.1, consists of a slender, constant cross section spar with an end-weight of negligible volume. In Fig.1 points C, B, and G are the geometric midpoint, the center of buoyancy, and the center of gravity, respectively.

Nomenclature

Symbol Suffixes:

- $_o$ water
- $_1$ spar material
- $_2$ end-weight
- $'$ stability limit
- $''$ sinking limit

a = spar cross sect. area
d = distance B to G
h = exposed length
ℓ = spar length
ℓ_2 = distance G to w_2
u = submerged length
u_2 = lgth. req'd to float w_2
w = weight
γ = specific weight

Specific Weights of Water:

$\gamma_o = 0.0361\ \text{lb/in}^3$ (fresh)

$\gamma_o = 0.0365\ \text{lb/in}^3$ (salt)

Dimensionless Parameters:

$D = d/\ell$
$F = w_2/w_1$ = weight ratio
$H = h/\ell$
$L = \ell/u_2$
$S = \gamma_1/\gamma_o$ = spar spec. gravity
$U = u/\ell$

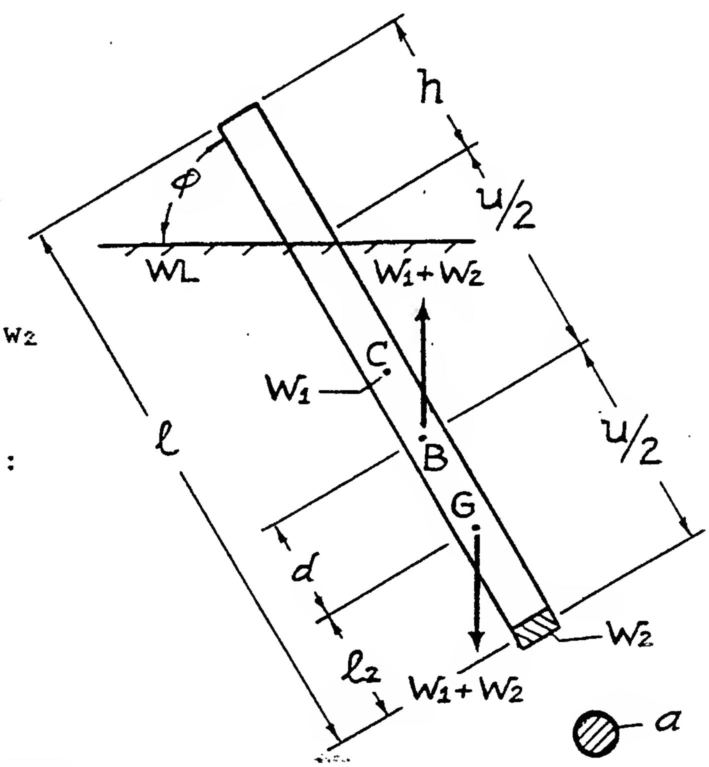

Fig.1 Analysis Model

PART B - ANALYSIS

Hydrostatics

The buoyancy force is directed upward and is equal to the weight of the floating body or to the weight of the displaced water, so $w_1+w_2=w_1(1+F)=\gamma_0 au$. The center of buoyancy is at the centroid of the displaced water volume, which, for a slender spar is at the midpoint of the submerged length. So point B will be a distance u/2 measured along the spar below the water line. We define u_2 as the length of spar required for floating w_2, so $w_2=\gamma_0 au_2$. The center of gravity G is located where the moments of the component weight forces balance, so $w_2\ell_2=w_1(\ell/2-\ell_2)$. By combining these relationships, we derive:

$$U = u/\ell = S(1+F) \tag{1}$$

$$H = h/\ell = (\ell-u)/\ell = 1-S(1+F) \tag{2}$$

$$D = d/\ell = (1/2)[S(1+F)-1/(1+F)] \tag{3}$$

$$L = \ell/u_2 = 1/SF \tag{4}$$

The righting couple is $(w_1+w_2)d\cos\varphi$ or $(w_1+w_2)D\ell\cos\varphi$ as shown in Fig.1. It follows that for definite vertical stability D>0, for neutral stability D=0, and for vertical instabilty or horizontal floating D<0. Furthermore, for definite flotation H>0, for neutral flotation or floating awash H=0, and for sinking H<0. The parameter L is the spar length per length required to float the end-weight w_2, so L is proportional to ℓ/w_2. Let F' be the weight ratio for which D=0, and let F'' be the weight ratio for which H=0. Then from eq.(3) with D=0 and from eq.(2) with H=0, we have

$$F' = \left[1/\sqrt{S} - 1\right] \tag{5}$$

$$F'' = (1/S) - 1 \quad . \tag{6}$$

Thus, **F'** is the lower and F'' the upper bound of weight ratios for a vertically stable, nonsinking end-weighted spar. The ratio of end-weight to spar weight for a proper boat hook must therefore satisfy the criterion

$$F' < F = w_2/w_1 <= F'' \quad . \tag{7}$$

We also have, by substituting F' into eqs.(2) and (4),

$$H' = 1 - \sqrt{S} \tag{8}$$

$$L' = 1 \Big/ \left[\sqrt{S} - S \right] \quad . \tag{9}$$

The parameters H' and L' express H and L for marginal stability weight ratios. They represent maximum achievable values in the sense that, with a ratio F slightly exceeding F', the design is barely stable and H and L approach H' and L', respectively. In Fig.3 the limiting weight ratios F' and F'' and the dimensionless lengths H' and L' are plotted versus specific gravity S. In this figure as one might expect, the F' and F'' curves divide the plot plane into regions of instability, stability, and sinking. Also as expected, the H' curve shows that greater above water exposure is possible with lower specific gravity spar materials. However, the L' curve is rather curious, it exhibits a minimum at S=0.25. Recall that L' is proportional to spar length per optimum end-weight. For a practical boat hook a long overall length is also desired in addition to stability, but this, it turns out, increases for S values both smaller and larger than S=0.25. Specific gravities less than 0.25 are representative of plastic foam materials and possibly balsa wood, none of which are relevant to the design. Specific gravities of common wood species lie in the range 0.4 to 0.8. Consequently, we have to conclude from the L' curve that denser wood for the spar lends itself better to the construction of longer proper boat hooks. This result was not expected.

Some numerical results are: For wood specific gravities from 0.4 to 0.8, only weight ratios between $F \approx 0.12$ and 0.58 produce optimum stable designs, the exposed lengths range from $0.11\ell'$ to $0.37\ell'$, and spar lengths go from $4.3w_2'/\gamma_0 a$ to $10.6w_2'/\gamma_0 a$, where w_2' is the smallest appropriate end-weight for stability.

Designing the Ultimate Boat Hook

One application difficulty stems from use of wood density values taken from reference books. These are often based on oven-dry conditions which are inappropriate to boating environments. The best determination of the actual specific gravity of a spar is made by measurement of its submerged length when vertically immersed in water. The specific gravity will then be the ratio of submerged length to overall length, or $S=u_1/\ell$. This is easily done by submerging and holding the spar vertically in water, releasing it momentarily, and marking the free floating waterline before it tips over. Small discrepancies between theory

and practice also arise because the analysis assumptions are nearly but not exactly satisfied. For example, the end fitting or weight has a small finite volume rather than zero volume, a wooden spar may not be of precisely constant cross section, nor is its density necessarily constant.

A typical design task, as in our custom boat shop, was the construction of the longest possible proper boat hook from a limited collection of spar materials while using an existing hook fitting. One should use a trial length equal to the theoretical, marginally stable spar length ℓ'. The formula for ℓ' follows from equating F' from eq.(5) to $F = w_2/w_1 = w_2/\gamma_o a S \ell'$.

$$\ell' = \frac{w_2}{\sqrt{S}\,(1-\sqrt{S}\,)\gamma_o a} \tag{10}$$

The trial length can then be modified in two ways to assure stability. A small reduction of the length ℓ' is one way. A second and better way is to taper a marginally stable spar over a length equal to the expected exposed length h'. If this is done its weight is reduced without altering the buoyancy force and a marginally stable design should thereby become stable without sacrificing any length. Tapering the spar below the waterline may not be helpful and is best avoided.

PART C - DESIGN EXAMPLE

A customer wanted us to make a proper boat hook for him using an existing bronze hook fitting and he wanted a hook as long as possible using traditional materials. We had an 11 3/4 oz. hook fitting and a 1 1/4 in. diameter wood spar of specific gravity $S=39/83=0.47$. This specific gravity was determined by vertically floating an 83 in. long sample and finding that 39 in. were submerged. So the trial length ℓ' and the theoretical exposed length h' without tapering were

$$\ell' = \frac{(11.75\ /16)}{\sqrt{39/83}\,(1-\sqrt{39/83})\ 0.0361\ (\pi/4)(1.25)^2} = 76.9 \text{ in.}$$

$$\text{and} \quad h' = 76.9(1-\sqrt{39/83}\,) = 24.2 \text{ in.}$$

We cut the spar to 77 in., fitted the hook, tested it in fresh water, and found it to be marginally unstable. It stood up vertically for perhaps 30 sec. exposing 24 in.

above the water but then slowly settled toward horizontal floatation. Tapering the upper end came next. We tapered 24 in. to a small diameter of about 7/8 in. A retest confirmed the analysis, it was definitely vertically stable with a handsome 27 in. portion above the water as expected of an ultimate boat hook. Its overall length with attached hook fitting was nearly 7 ft. Fig.2 shows this boat hook.

Our customer was satisfied with a 7 ft. boat hook. Had he requested one 8 1/2 ft. long overall utilizing an 8 ft. long wood spar with the same hook fitting, then only a denser wood could achieve this design requirement. The required S value can be calculated by solving eq.(10) for S. The two solutions of eq.(10) are always real and they are given by

$$S = [0.5-(w_2/\gamma_o a \ell')] \pm \sqrt{[0.5-(w_2/\gamma_o a \ell')]^2-(w_2/\gamma_o a \ell')^2} \quad (11)$$

Using numerical values identical to those for the 7 ft. boat hook, except for ℓ' which is now 8 ft or 96 in., eq.(11) becomes

$$S=(0.5-0.1726)\pm\sqrt{(0.5-0.1726)^2-(0.1726)^2}=0.606 \text{ and } 0.049.$$

The numerical answer, S=0.606, is practical; some common woods have specific gravities in this range. The exposed length h' would now be 21.3 in., which is somewhat shorter than the 24.2 in. of the previous example. The other numerical answer, S=0.049, calls for an unrealistically small specific gravity.

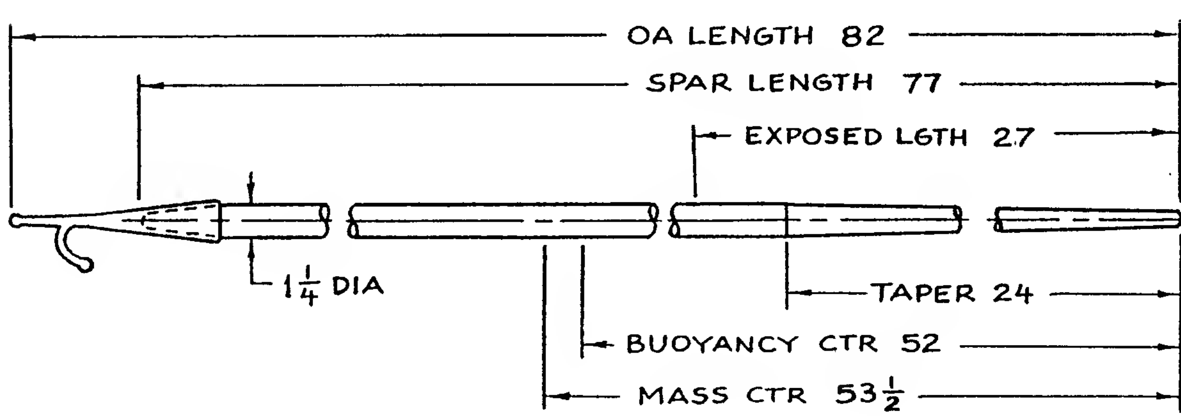

Fig.2 Ultimate Boat Hook - The Detailed Example

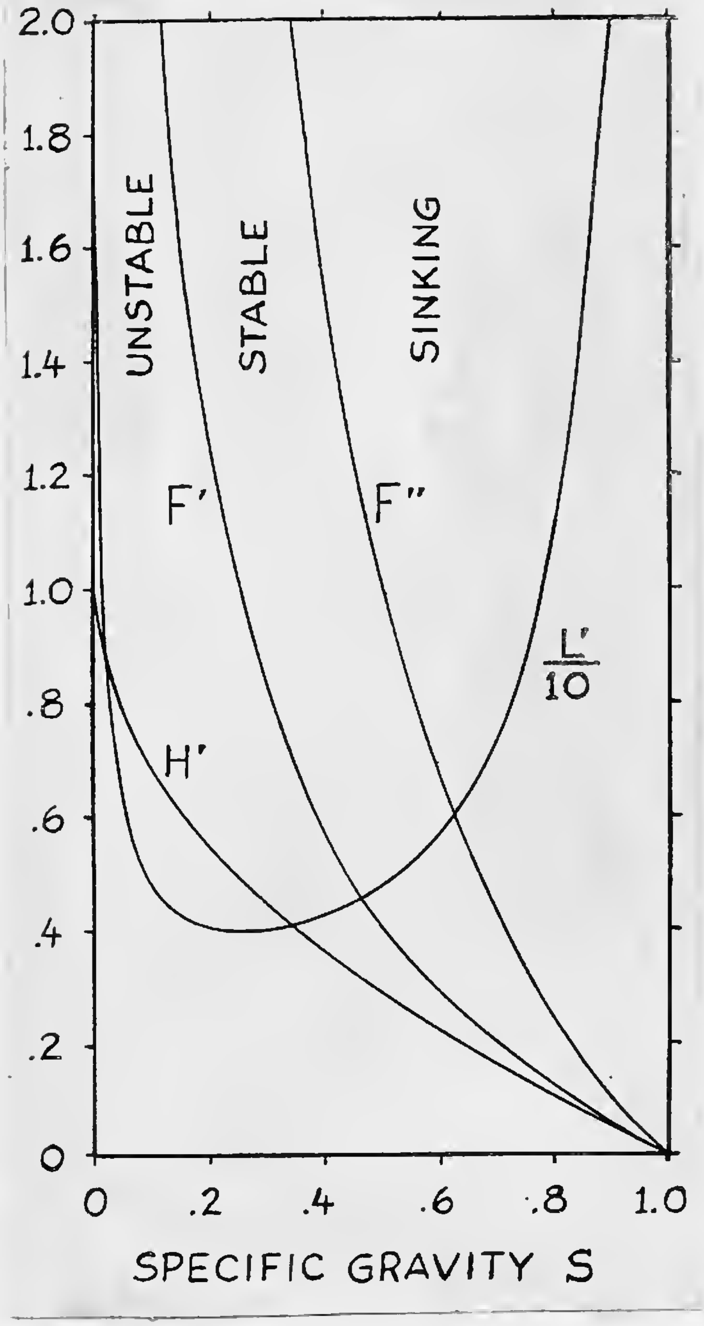

Fig.3 Dimensionless Parameters Versus Specific Gravity

Fig.4 Stable, Floating, Ultimate Boat Hook

INSTRUCTOR'S NOTE

ABSTRACT: DESIGN OF A VERTICALLY FLOATING BOAT HOOK

R. H. Koebke 1995

The design of a vertically floating boat hook having the useful property of righting itself when accidentally cast overboard, is not difficult after one has analyzed the problem. But, I found that almost everyone approaches the design with the cavalier attidude that it is trivial. A model is then quickly constructed with expectations that a good design will emerge after some trial and error adjustments. Unfortunately, this is likely to be disappointing, because it is difficult to discover through experimentation what the critical parameters are. The Case Study introduces the design problem in Part A, offers an analysis in Part B, and describes a practical design in Part C.

A 3 page Instructor's Note suggests an introduction of the design problem and a possible dialog between the instructor and designers. The dialog provides statements, questions, and answers to help put the designer's thinking on the right track. Two model construction exercises are offered. Providing only Part A of the Case Study to designers is one way to assign this design problem as an exercise.

Editor's Note

An additional suggestion is to give students only the first page of Part A and let them develop the analysis model shown in Fig. 1.

INSTRUCTOR'S NOTE

For Case Study: DESIGN OF A VERTICALLY FLOATING BOAT HOOK

One might introduce the problem by explaining what a boat hook is, that it is used from a boat for reaching over side to catch a mooring line or other object, and that it is occasionally dropped overboard. Most boat hooks float flat in the water, they are then difficult to retrieve because, in larger craft, the freeboard is higher than an arm's length and, in small craft, leaning far over the side is hazardous. "Now wouldn't it be convenient to have a vertically floating boat hook? It could be retrieved so much more easily".

Boat hooks should be at least 6 ft. long to be useful, but longer is better. They are often 1 1/4 in. in diameter. Solid wood shafts are traditional and best because they can't fill up with water and sink as tubular metal ones sometimes do. Bronze or galvanized iron boat hook fittings typically weigh about 12 oz. Unfortunately the specific gravity of woods cannot be reliably specified, there are significant differences among species and moisture content confounds tabulated values. A specific gravity of 0.4 is quite light, 0.8 is heavy.

Instructors might consider handing out only PART A of the case study to students, this sets the problem without giving away the solution.

A dialog between students and instructor might include the following statements (S), questions (Q), and answers (A).

S: Consider a plain wooden shaft of density equal to 1/2 the density of water. It floats horizontally in water.

Q: How much volume is above water, where are the centers of gravity and buoyancy located, and how much weight must be added to the shaft to just sink it?

A: 1/2. Both at midlength. Equal to the wood weight.

S: A concentrated weight equal to 1/3 the wood weight is attached to one end of the shaft. This weight will not sink the assembly.

Q: Where is the center of gravity now, describe the size

and geometry of the submerged volume and the location of the center of buoyancy?

A: 3/8 of length from weighted end. 2/3 of the shaft volume. It is roughly wedge shaped, but its precise geometry requires further, awkward analysis. The buoyancy center has moved toward the weighted end. Its location depends on the geometry of the submerged volume.

S: Please appreciate that the calculation of the submerged volume of a long, floating cylinder whose axis is slightly tipped from the horizontal is awkward. The degree of tilt depends on the location of the buoyancy center which itself depends on the shape of the volume one wishes to calculate.

Q: Can this awkward calculation be avoided?

A: Yes. Approach the stability problem of a long, weighted, floating cylinder by considering it to be initially in a vertical position. Then ask, will it stay that way.

S: Visualize the same shaft assembly to be immersed vertically in water while held by a vertical guide.

Q: How much length will be submerged and where is the the center of buoyancy now?

A: 2/3 of the length. 1/2 of 2/3 or 1/3 length from the weighted end.

Q: If the vertical guide is removed will the assembly remain vertical or tip over?

A: It will tip over, because the CG at 3/8 length from the end is above the buoyancy center at 1/3 length from the end.

Attempts to design boat hooks having the desired properties by starting with models but foregoing prior analysis are likely to be disappointing, yet this may be instructive. One finds out the hard way that lengths and weights applicable to one wood sample may not work for another, and the relationships for achieving a maximum length of the wood

spar above the water surface will probably remain a mystery. However, model building is simple and inexpensive in this case.

Although I have not tried it myself, I propose giving students two long wooden sticks of different densities and one small weight they must use. Their assignment will then be to experiment with one stick, to cut it progressive shorter so that at some stage it will begin to float vertically. Then, based on their findings, but without expermentation on the second stick, they are cut the second stick so that it floats vertically with maximum possible exposure above the water. A float test of the second stick should demonstrate that this is not a trivial exercise.

I have tried a model made of a 6 ft. length of 3/4 in. CPVC pipe with CPVC pipe caps. One cap was bonded to the pipe and the other cap attached only by friction so it could be removed. Floating the assembly in water with different loads of lead shot demonstrated convincingly that for a wide range of end-weights there is horizontal flotation. When the critical weight is reached only a very small increment will result in vertical flotation and increments after that will quickly reduce the exposed length. This model, a fixed length - variable end-weight combination, does not correspond to the practical and more difficult boat hook design task where the end-weight is fixed and the spar length has to be adjusted appropriately, but it is easy to construct. This CPVC pipe model lends itself very nicely to verifications of theory. It is perfectly round, straight, and of uniform density so the water line and the CG and buoyancy center will fall precisely at the predicted locations.

The analysis only requires understanding of solid body statics, fluid statics, and a little algebra. The geometry is practically one-dimensional, hence the mathematical formulation is simple.

Most persons will probably begin the analysis with dimensioned parameters, using inches, ounces, and pounds, or meters, kilograms, and Newtons, but this can quickly turn into a numerical quagmire. I suggest this is a case for demonstrating the convenience of dimensionless parameters.

R. H. Koebke